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Urban wind energy exploitation systems: Behaviour under multidirectional flow conditions—Opportunities and challenges

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ABSTRACT

The growth of the world energy demand, the limited fossil fuel reserves and the increasing greenhouse gas emissions require improvements in energy-generation technologies. Specifically, urban wind energy is a source with great potential that is currently being wasted.

The characteristics of urban wind and perspectives and proposals to exploit it have been researched and analysed in the literature. The results show that urban winds have a strong multidirectional component that requires analysing the wind turbine behaviour. To explain the influence of the multidirectional wind on the turbine, a simulation of the air flow around a building section was performed, the sections of various wind turbines were superimposed on the velocity fields, and their aerodynamic behaviour was qualitatively studied.

The results show that horizontal-axis wind turbines have better performance in flat-terrain applications, whereas in high-density building environments, the superiority of vertical-axis wind turbines is demonstrated.

The main benefits of urban wind power development are: distributed power generation, the use of a renewable energy source, and the technological and economic exploitation of building roofs.

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1. Introduction

According to International Energy Agency (IEA) estimates [1], the world demand for primary energy is expected to double over the period 1990–2035 (Fig. 1).

Faced with the exhaustion of traditional energy sources (fossil fuels and nuclear fission), to satisfy the predicted demand, energy sources must be exploited in new ways, especially renewable energy sources. An example is wind-based energy generation, which has grown exponentially since 1995 (Fig. 2), from 4778 MW in 1995 to 160,084 MW in 2009 [3].

Most of the power shown in Fig. 2 comes from flat-terrain installations. However, the urban environment also has great potential for wind power that has not been harnessed [4]. In

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urban areas, there is a multiplication factor of the wind speed because of the presence of buildings, but the turbulence intensity and the multidirectionality also severely increase, which is an aspect that requires special attention [5–8]. Additionally, these installations increase the profitability of the external surfaces, i.e., the roof and the walls, which currently serve only to enclose the building.

Another advantage of exploiting wind energy in urban environments is its proximity to the consumption points (distributed electric power generation). Distributed generation offers significant benefits in terms of high energy efficiency, lower emissions (of pollutants), reduced energy dependence and stimulation of the economy [9]. The optimisation of distributed generation requires voltage profile improvements, the reduction of electric energy flow in power lines (with the associated reduction of energy losses in power lines and electric devices), and the increase of the energy source availability [10]. The reduction of greenhouse gas emissions is another significant factor [11].

Water consumption, a limited resource in some regions, is reduced with the exploitation of the wind power. Table 1 shows a comparison of the water consumption associated with various energy technologies.

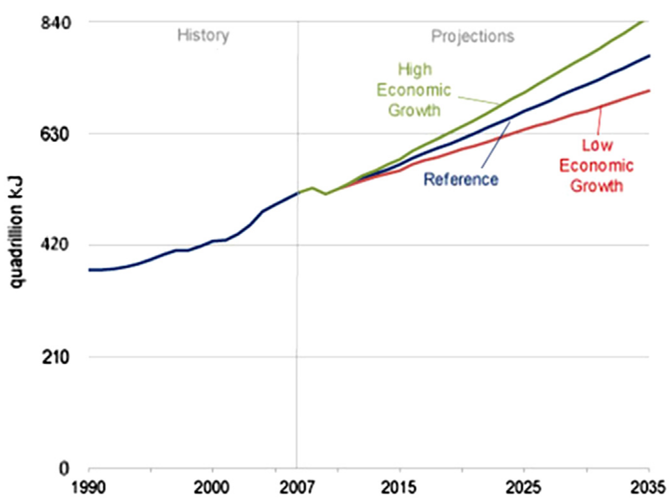

Fig. 1. Estimate of the world demand for primary energy for the period 1990–2035, considering three base scenarios [2].

Despite the great positive impact of wind power, this energy source has disadvantages. One of the shortcomings is the visual impact. However, urban buildings and their auxiliary facilities (e.g., chimneys and aerials) share the visual impact with the wind turbines, minimising it. Additionally, the wind generators can be architecturally integrated.

Noise emissions, both audible and infrasound, are a significant environmental factor to consider. Most of the noise pollution comes from conversion and generation machinery, although the blades of horizontal-axis wind turbines (HAWT) also cause noise when they interact with the tower structure (especially with leeward working conditions) [5]. At high wind velocities, the noise due to the forced circulation of the wind around the building and its associated facilities is higher than the noise generated by the wind turbine (Fig. 3) [13].

Wind-powered generators also generate infrasound (with frequencies above 16 Hz) and low frequency vibrations that can be transmitted to the building structure [5]. These vibrations can be tolerated by industrial buildings, but they can cause problems in residential buildings [5]. This aspect highly varies depending on both the generator and the building characteristics, and it must be analysed case by case.

The impact of wind turbines on birds is very important in flat-terrain wind facilities [12,14], but its repercussions are smaller in urban environments because of other anthropogenic factors that have a greater impact.

Wind power can also affect TV and radio reception [12,14,15]. This is due to the periodic modulation of the electromagnetic fields by means of reflection, absorption and dispersion by the blades [12]. In urban environments, this impact is lower because of the building volumes, which are greater in size than the wind turbines. Any mobile or stationary structure generates interference

Table 1
Water consumption of various energy technologies [12].

Technology	Litters/kW h
Nuclear	2.30
Coal	1.90
Oil	1.60
Combined cycle gas	0.95
Wind	0.004
Solar	0.110

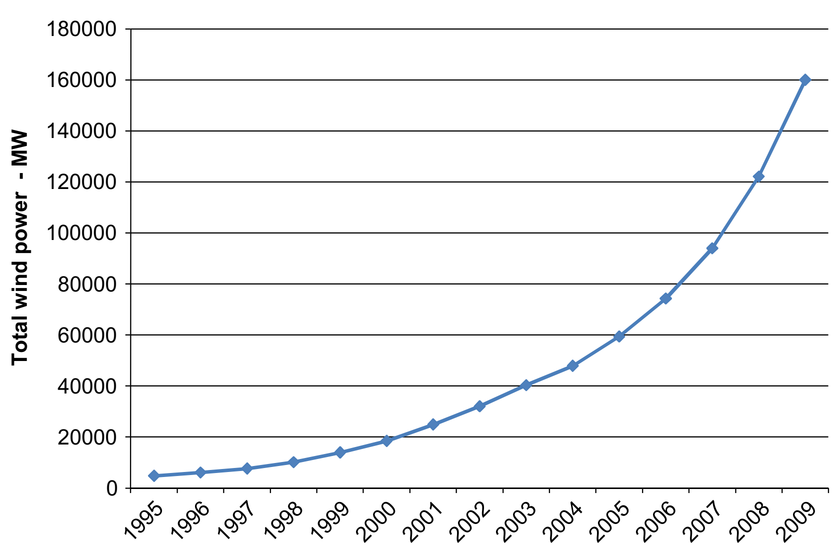

Fig. 2. Evolution of global installed wind power [3].

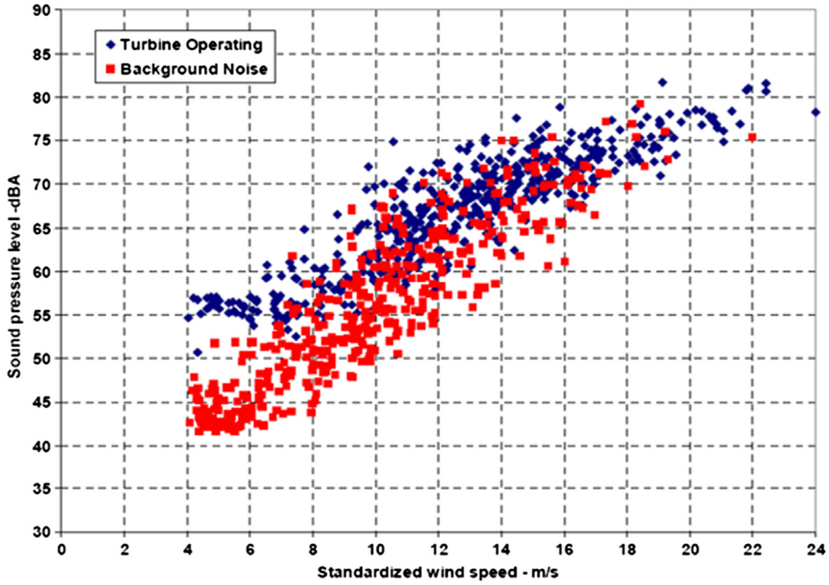

Fig. 3. Example of sound levels vs. wind speed for small wind turbines [13].

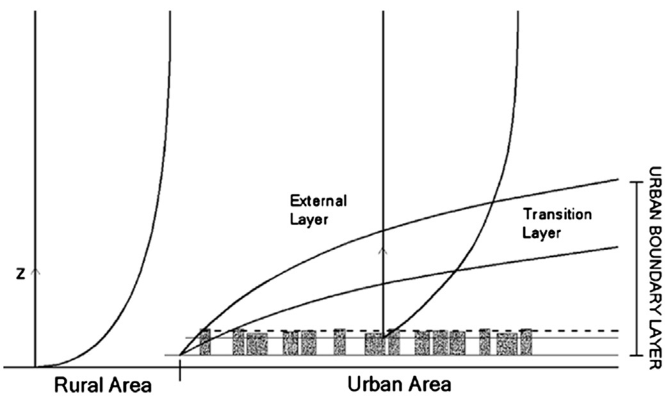

Fig. 4. Urban boundary layer and velocity profile in urban environments (right) and flat terrain (left) [16].

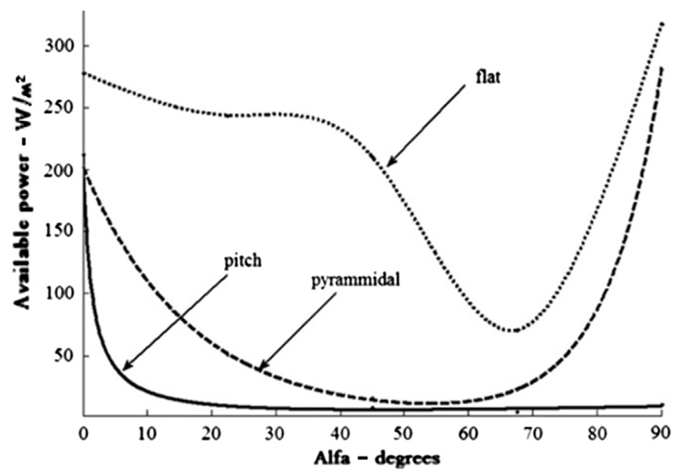

Fig. 5. Power density dependence on the incident wind angle for flat, pitched and pyramidal roofs. In all three cases, the wind turbine position is at a corner of the roof [6].

with the electromagnetic signals [14]. However, both the low power and size of urban wind turbines lessen this impact because the intensity of the interference has a direct relationship with the obstacle size [15].

Mechanical safety is also a fundamental aspect to consider. For each wind turbine, an analysis of the resistance to fatigue of both the structural (including the building structure) and mobile components (especially the blades) must be conducted [5]. The detachment of a blade (or a part of it) can cause a very serious accident because of the substantial momentum [5]. However, according to Grauthoff [5], the probability of a blade breaking, striking a person and causing injuries (independent of the distance it covers) is extremely low, and the author did not advise establishing a safety perimeter around the wind turbine outside of the facility. Grauthoff [5] advises establishing a safety perimeter only in the case of hazardous industries.

Faced with the potential of urban wind energy exploitation, this work presents bibliographic research on the perspectives of various authors regarding this topic and their proposed solutions. The proposed solutions to urban wind energy exploitation have been analysed, and their advantages and disadvantages are discussed.

In Section 2, urban wind characteristics and the effects of buildings are discussed, and a computational fluid dynamics (CFD) simulation of the air flow around a vertical section of a flat-roof building is presented. In Section 3, proposals for wind energy exploitation on buildings and large structures are described, and turbine sections are superimposed over the velocity field obtained from the simulation to analyse their behaviour. Section 4 presents a discussion on the significance of the multi-directional character of the wind for the various types of turbines. Finally, in Section 5 the conclusions of the research are summarized.

2. Characteristics of the wind in the urban environment

The terrain is rougher in urban environments, which modifies the incident velocity field. This is shown in Fig. 4, where the urban boundary layer is also represented.

The average velocity of the wind is lower in urban environments than over flat terrain [16]. Additionally, in the urban environment the turbulence intensity is substantially higher, which transmits additional loads to the wind turbines [6].

Fig. 6. Diagram of the simulation case (left) and a symmetric building with a large length with respect to its height (right). The simulation comprises the central length of the building.

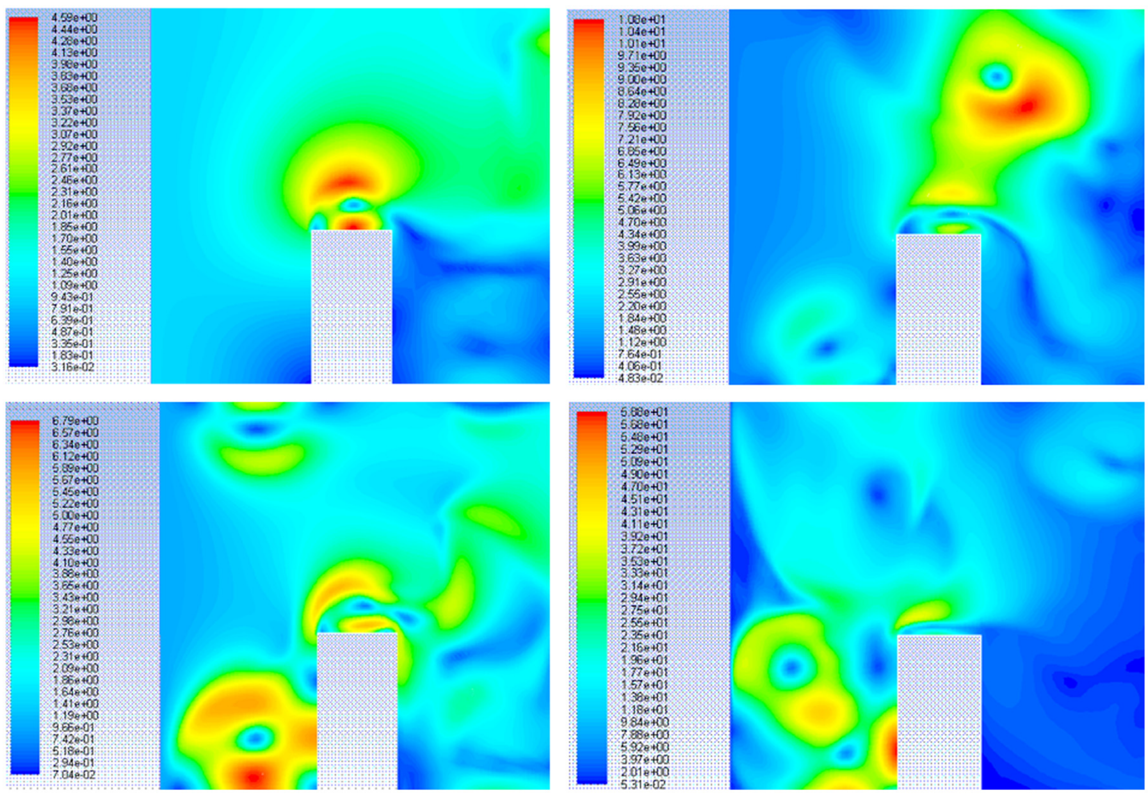

Fig. 7. Instantaneous velocity (m/s) maps obtained in the simulation for incident wind velocities of 1, 2, 4 and 10 m/s (from left to right and from the top to the bottom).

Fig. 8. HAWT at the Bolte Bridge [20] (left) and an example of a BAWT (right).

Moreover, around the buildings, regions with significant wind velocity intensities are created [6,7,16,17], which entail higher local average velocities [6,7,17].

Several authors such as Ledo et al. [6] and Lu and Ip [7] describe the influence of the buildings on both the wind velocity and turbulence intensity from results obtained in CFD simulations. These kinds of studies are essential for determining both the optimal location and the wind turbine model. In these studies, four types of roofs were analysed: flat, sloped, pitched and pyramidal roofs. The results show that, considering both velocity distributions and turbulence intensity, flat roofs are more attractive for installing wind turbines [6]. Sloped roofs are also interesting, and a wind turbine could be installed on the top edge because both high velocities and low turbulence intensities are present [7]. Abohela et al. [18] demonstrated the interest of both vaulted and domed roofs because of the lower turbulence and the intensification factor, although these shapes are used infrequently.

Ledo et al. [6] present an estimate of the power density available in flat, pitched and pyramidal roofs (Fig. 5). The power density is clearly higher in the flat roof case.

The concentration factor of the wind caused by the building shape can increase the local average velocity of the wind from 1.5 to 2 times and the power density 3–8 times in certain zones of the building [7].

Applying the same criterion in the urban environment as in flat terrain, because of the velocity profile of the wind, the tower of the wind turbine must be between 20 (in low-density building zones) and 40 m (in high-density building zones) higher and highly reinforced to resist the high intensity of the turbulence [5]. The height requirement can be satisfied by installing the wind turbine on a high-rise building [7].

Turbulence is transmitted to the wind turbine tower and from the tower to the building structure, so for high-power facilities, the structure may have to be reinforced. As a solution to this problem, there have been proposals to integrate the wind power system into the building design and use a higher number of low-power wind turbines to distribute the loads transmitted to the structure [5].

Because in the urban environment the wind velocity is highly variable and its behaviour is extremely turbulent, an urban wind turbine must be designed appropriately to operate under these conditions.

To analyse the influence of the multidirectional urban wind on the different types of turbines, a 2D simulation of the wind circulation around a vertical section of a long-short building was conducted using the computational fluid dynamics software Ansys Fluent-Workbench. Fig. 6 left shows a diagram of the simulation case. The geometry was tested for incident wind velocities (U) of 1, 2, 4 and 10 m/s. Standard values were used for both the air density (ρ) and the viscosity (μ). To validate the results, the central length of a symmetric building with a length (L) much larger than its height (H), or $L \ggg H$, must be considered, as shown in Fig. 6 right.

In the urban environment, the intensity of the turbulence and the multidirectional character of the wind are more important than the incident velocity. Significant variations in both the direction and the velocity of the wind appear close to the building surfaces for small variations of the incident wind velocity. Fig. 7 shows the velocity maps obtained for incident wind velocities of 1, 2, 4 and 10 m/s.

The simulation results show that the air flow is highly unstable and multidirectional. Small variations in the incident wind velocity cause large variations in the local velocity distribution. A local intensification factor is clearly observed close to the building surfaces that can multiply the incident wind velocity by 6 in certain zones.

A vortex is formed on the building roof that is very sensitive to the incident velocity variation and is clearly defined for lower incident velocities. For higher incident velocities, both dragging and dispersion of this vortex are observed. Above approximately

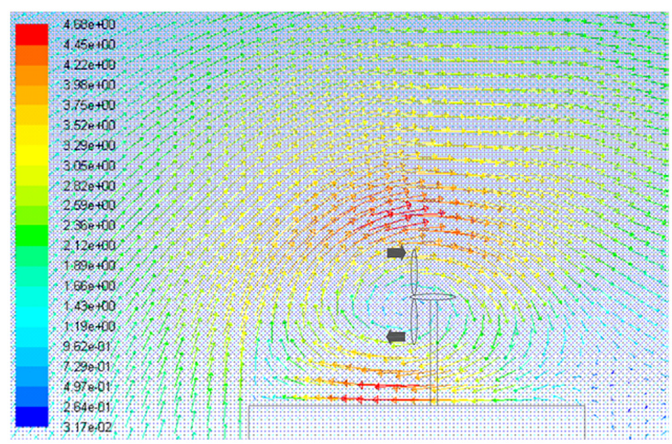

Fig. 10. Superposition of a HAWT over the air flow for an incident velocity of 1 m/s.

Fig. 9. DAWT.

2 m/s, the vortices on the roof are projected upward. Likewise, a vortex appears in front of the upstream wall of the building.

Results obtained in other studies such as those from Ledo et al. [6], Lu and Ip [7], Abohela et al. [18] or Watson [19] validate the results of this simulation. A stable atmosphere was assumed in these simulations [6,7,18,19], although additional strong disturbances appear in actual cases. In the highly variable conditions of the actual urban wind, with sudden changes in both the direction and the velocity in a very short time, the presence of turbulence is high. This is the reason that the qualitative analysis of the wind turbine behaviour under urban wind conditions is of great interest.

To analyse the multidirectional wind conditions that the turbines are subjected to on a building roof, in Section 3.2 the turbine sections are superimposed on the velocity field obtained from the simulation. To obtain a clearer graphic representation, the map of the velocity distribution for an incident wind velocity of 1 m/s is used because the vortex on the building roof is clearly defined. Analogous conclusions are obtained with other conditions (velocity and direction) of the incident wind.

Fig. 11. Hybrid VAWT generator (Darrieus and Savonius) [32].

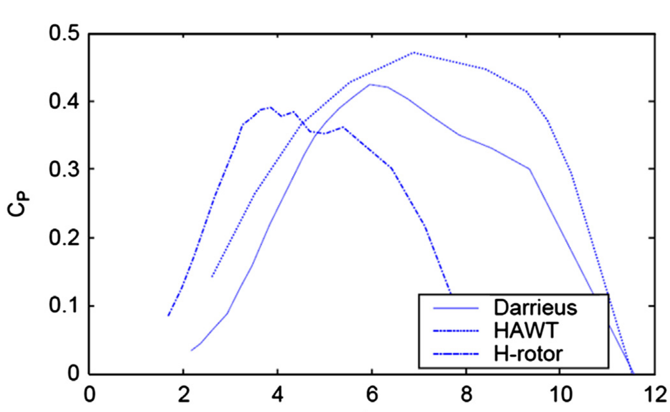

Fig. 12. Power coefficients C_p vs. the specific velocity λ for three turbines: HAWT, Darrieus and H-rotor [26].

3. Wind energy exploitation systems in anthropogenic environments

This section is focused on the proposed solutions for wind power exploitation in anthropogenic environments. The urban environment is the core of this section (Section 3.2), but large structures are also considered (Section 3.1) as an intermediate case between the urban environment and flat terrain.

Table 2
Summary of the main differences between three turbines: HAWT, Darrieus and H-rotor [26].

	H-rotor	Darrieus	HAWT
Blade profile	Simple	Complicated	Complicated
Yaw mechanism needed	No	No	Yes
Pitch mechanism possible	Yes	No	Yes
Tower	Yes	No	Yes
Guy wires	Optional	Yes	No
Noise	Low	Moderate	High
Blade area	Moderate	Large	Small
Generator position	On ground	On ground	On top of tower
Blade load	Moderate	Low	High
Self-starting	No	No	Yes
Tower interference	Small	Small	Large
Foundation	Moderate	Simple	Extensive
Overall structure	Simple	Simple	Complicated

Fig. 13. Giromill wind turbine with five blades.

3.1. Structure-associated wind power systems

Large structures (such as bridges and oil platforms) can be considered as intermediate applications between flat terrain and the urban environment. That is, the structure disturbs the air flow although the external environment can be flat terrain.

Oppenheim [20] describes a representative example of wind turbine integration into a structure, specifically the Bolte Bridge in Melbourne (Australia). This study [20] shows the results of the analysis of three options:

(1) The first option is a vertical-axis wind turbine (VAWT) with a capacity of 0.6 MW installed between two columns of the bridge structure. According to Oppenheim, the main advantage of the VAWT is aesthetic. VAWTs within this power range present considerable technical difficulties, and they are not produced on a commercial scale. Oppenheim [20] estimates that this turbine can generate 2 GW h/year and reduce CO_2 emissions by 3000 t/year.
(2) The second option is a diffuser-augmented wind turbine (DAWT), also installed between two columns of the structure. According to Oppenheim [20], this option is also aesthetically attractive, but it presents technical difficulties because of the impossibility of changing the direction. The power generated by this turbine is unacceptably low because of the fixed direction of the rotor [20].
(3) The third option is a horizontal-axis wind turbine (HAWT) with a capacity of 2 MW installed above the bridge structure (Fig. 8 left). This option is the most technically viable, and the power generated is the highest of the three options, estimated to be 8 GW h/year, the equivalent to 10,500 t/year of CO_2 emissions saved or 210,000 t in the 20 years of operation of the wind turbine. This proposal is also economically feasible, with a return period of 8–9 years and a profit in the 20 years of operation of 10 million dollars [20].

The case of the wind energy exploitation with large structures is similar to flat-terrain applications regarding wind characteristics. Hence, the HAWT installation is advantageous because of the higher power coefficient (performance) under unidirectional wind conditions.

3.2. Building-associated wind power systems

As explained in Section 2, the wind has a significant irregularity (undergoing a concentration effect in certain zones) and high-intensity turbulence in urban environments. With these considerations, the previous studies that assumed flat terrain do not apply. This presents an opportunity for innovation and development because innovative alternatives are required for wind energy exploitation in high building density zones. Several authors such as Dayan [21] and Mertens [22] mention the suitability of the VAWT in this environment because of its higher efficiency under turbulent wind conditions [20–25].

The main alternatives for wind energy exploitation in urban settings are analysed in the following.

3.2.1. Building-augmented wind turbines (BAWT)

Mertens [22] describes the advantages of the architectural integration of wind turbines into buildings, showing how the building can be designed to generate a multiplication factor of the wind to enhance wind energy exploitation. These are referred to as building-augmented wind turbines (BAWT). Although the strict meaning of this expression covers several methods of building wind exploitation, the most representative sense is that in which the wind turbines are integrated into the building morphology. Fig. 8 right shows an example of a BAWT. The main advantages are the aesthetic factor and the wind power concentration. In contrast,

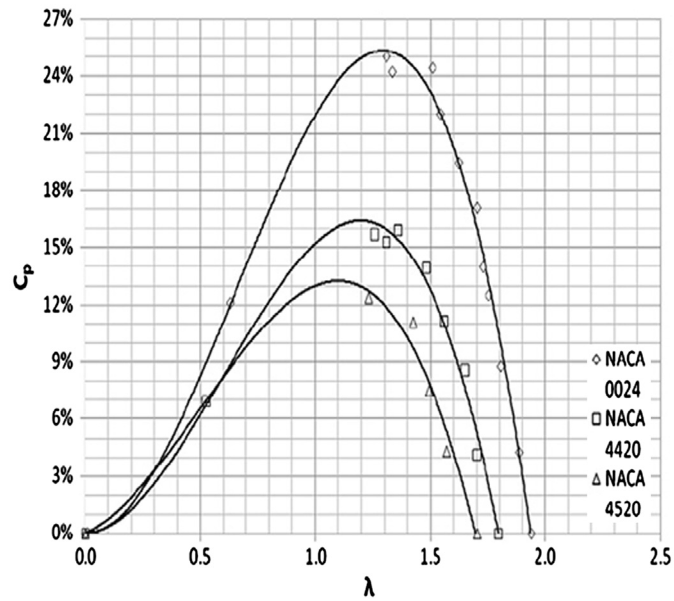

Fig. 15. Power coefficients C_p vs. the specific velocity λ for three types of blades, Giromill wind turbine with four blades [34].

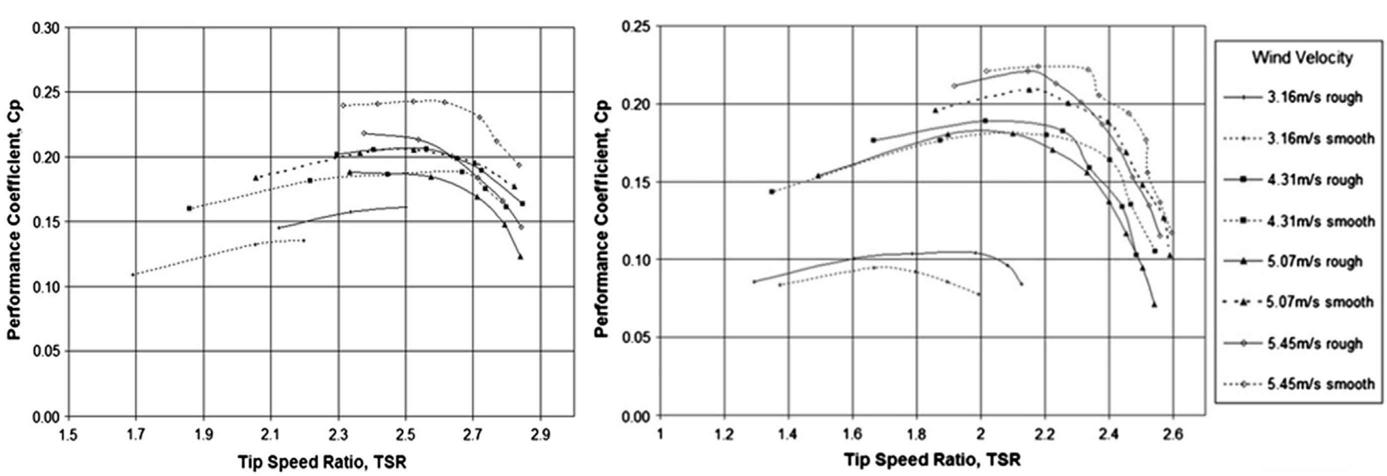

Fig. 14. Power coefficient of a Giromill wind turbine with two (left) and three (right) blades [33].

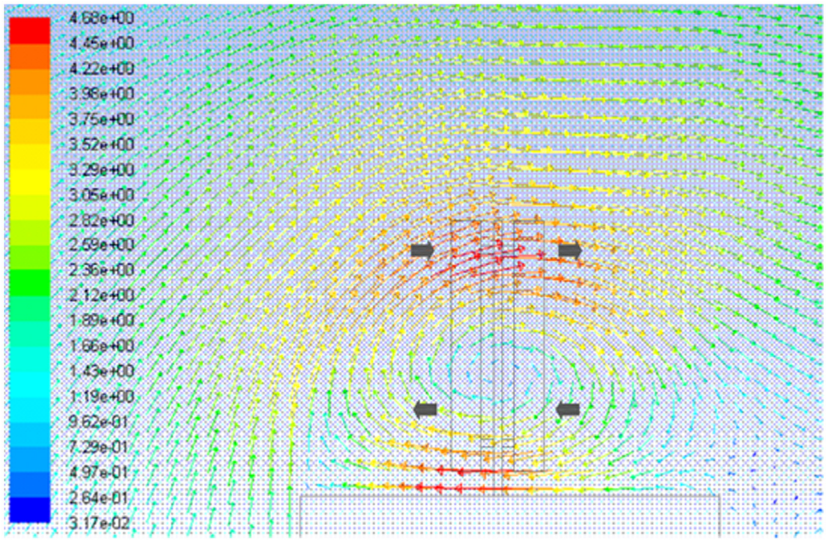

Fig. 16. Superposition of a VAWT over the air flow for an incident velocity of 1 m/s.

Fig. 17. Helical Darrieus wind turbine.

the single direction of both the wind concentration configuration and the wind turbine (direction consistent with town-planning criteria) causes substantial waste when the wind direction differs from that of the design.

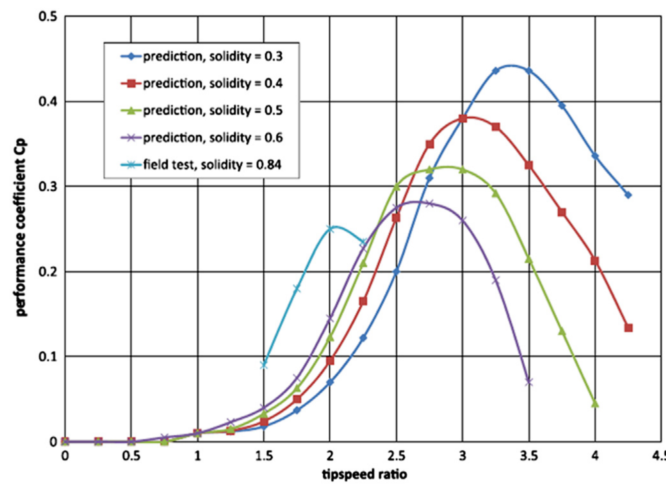

Fig. 18. Power coefficient for various solidities, helical Darrieus wind turbine [35].

3.2.2. Horizontal-axis wind turbines (HAWT)

HAWTs have lower performance under high-turbulence conditions [20,26], and they are mainly recommended for very open areas or isolated buildings [27]. The high variability of the wind direction in the urban environment is an additional disadvantage because with lower wind velocities, the start-up time is greater [28]. The wind turbine must be installed at a greater height as its swept area increases to reduce the exposure to turbulence [27]. Consequently, this kind of wind turbine is more appropriate for installations on large structures (as mentioned in Section 3.1) or in zones with low building densities.

Using wind diffusers, HAWTs can operate with lower wind velocities, and they can better resist turbulence [29,30]. This type of wind turbine is called a diffuser-augmented wind turbine (DAWT).

Wang et al. [29,30] comment that by using a diffuser-concentrator, the wind velocity can be multiplied by 1.5 and the power by 2.2. These wind turbines (Fig. 9) can be installed in a higher building density zone than a HAWT without a diffuser, but the orientation requirement is a disadvantage compared with the VAWT. Stable and unidirectional wind conditions were assumed in the studies of Wang et al. [29,30]. These assumptions do not reflect the actual behaviour of the wind in the urban environment,

where the turbulence is intense and the wind is very variable. These aspects are more favourable for VAWTs.

Fig. 10 shows the superposition of a HAWT over the air flow for an incident velocity of 1 m/s. The represented conditions show an incompatibility with wind turbine operation, and they could even cause damage to the turbine, with the consequent risk of an accident.

3.2.3. Vertical-axis wind turbines (VAWT)

Riegler [31] comments that for applications of less than 10 kW, VAWTs have significant advantages over HAWTs. These advantages increase in high-turbulence zones such the urban environment. Additionally, VAWTs generate lower noise emissions, and they are less expensive in terms of both construction and maintenance. Riegler [31] additionally mentions the importance of the hybrid VAWT (Fig. 11), which combines the principles of traditional VAWTs (such as Darrieus and Savonius wind turbines) to improve its weaknesses.

Eriksson et al. [26] present a comparative analysis of two VAWTs (a Darrieus and an H-rotor, or Giromill) and a HAWT. As shown in Fig. 12, the HAWT has a higher power coefficient (although the three values are similar), but there are several factors that make the VAWT technology more advantageous [26]. In Table 2, a summary of the main differences between the three systems analysed by Eriksson et al. [26] is shown. Among the main technical advantages of the VAWT are the better behaviour under highly turbulent wind conditions, the absence of a direction control mechanism (omnidirectional turbines), the lower noise emissions (because of the lower rotational speed, as shown in Fig. 12, and the position of the electric machinery at the base), the

Fig. 19. Flexible Darrieus wind turbine in both horizontal (left) and vertical (right) positions [36].

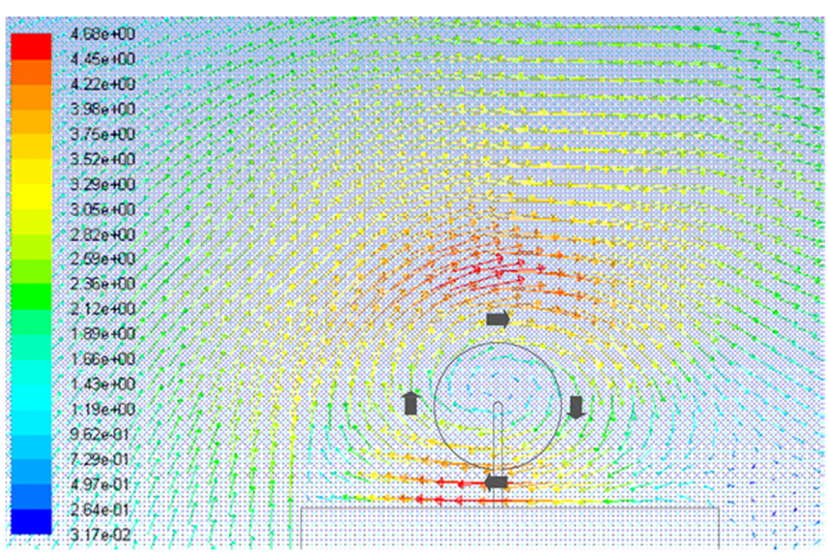

Fig. 20. Superposition of a horizontal Darrieus wind turbine for an incident velocity of 1 m/s.

lower vibrations transmitted to the structure, the lower cost of both construction and maintenance, and the greater simplicity of the structures [26].

Howell et al. [33] present a study of a Giromill, or H-rotor, wind turbine (Fig. 13), a variant of the Darrieus rotor. The results (Fig. 14) show that the power coefficient depends on the material roughness. A study conducted by El-Samanoudy et al. [34] highlights the great influence of the blade type on the power coefficient (Fig. 15).

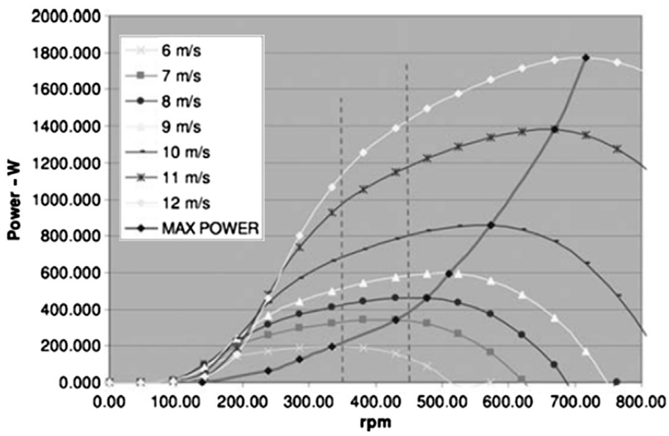

Fig. 21. Power vs. rotation speed for various wind velocities, flexible Darrieus wind turbine [36].

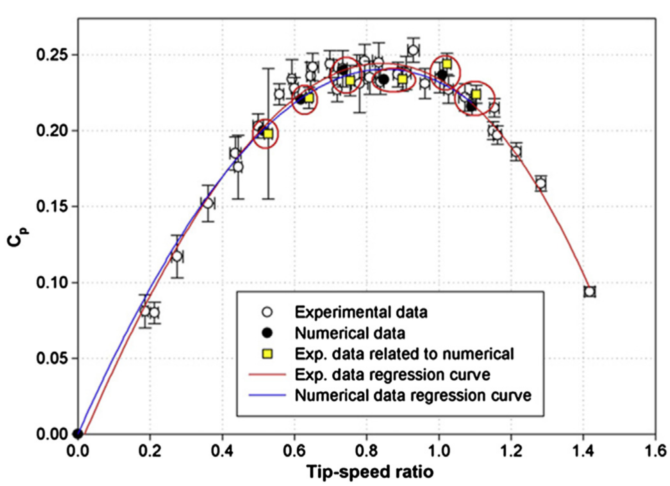

Fig. 22. Power coefficient C_p of the Savonius wind turbine [37].

Fig. 16 shows the superposition of a generic VAWT (valid for Darrieus, Giromill or Savonius) over the air flow for an incident velocity of 1 m/s. The represented conditions are compatible with wind turbine operation. However, although the multidirectionality of the wind is a normal situation in urban environments, quantitative tests of wind turbine behaviour under these conditions are not found in the literature.

Kirke and Lazauskas [35] present a study of the helical Darrieus wind turbine (Fig. 17). The helical shape results in a variable pitch that generates a high starting torque (the starting torque of the fixed-pitch Darrieus turbine is insufficient for self-starting), a higher efficiency and reduced vibrations, although the active velocity control systems are more complicated and expensive [35]. This study concludes that the lower solidity of the blades increases both peak efficiency and tip-speed ratio, as shown in Fig. 18.

Sharpe and Proven [36] propose a Darrieus wind turbine with flexible blades. This wind turbine can be installed either vertically or horizontally, as shown in Fig. 19. The streamlined support structure performs the function of wind concentration [19,36]. The main advantages of the flexible blades are the efficiency increase and the reduction of the vibrations transmitted to the building structure [36].

Fig. 20 shows the superposition of a horizontal Darrieus wind turbine for an incident velocity of 1 m/s. The represented conditions are appropriate for turbine operation, and furthermore, its behaviour improves under omnidirectional wind conditions.

Because of the low solidity of the blades of the fixed-pitch flexible Darrieus, the wind turbine must work with a variable tip speed to take advantage of the highest power coefficient peaks (Fig. 21) to achieve a substantial efficiency increase, which implies a higher level of sophistication in the active velocity control system.

Alessandro et al. [37] conducted a study of the Savonius wind turbine. Compared with other wind turbines, it has a lower power coefficient (Fig. 22), although it has advantages in that it is self-starting and does not have to change direction (omnidirectional) [37]. Another great advantage is that it is extremely simple to construct, and hence it can be extremely low-cost (recycled containers, pipes or barrels can be used in its construction). This feature would be very attractive in zones with extremely low economic resources (Fig. 23 left). The possibility of using recycled materials confers to this technology a highly sustainable character.

The modifications of Savonius wind turbines that increase the power coefficient have an important role, especially the variation of the number of blades, the interposition of obstacles and the helical shape [37,38].

Mohamed et al. [38] present an analysis of Savonius wind turbines with two and three blades and with a deflector sheet

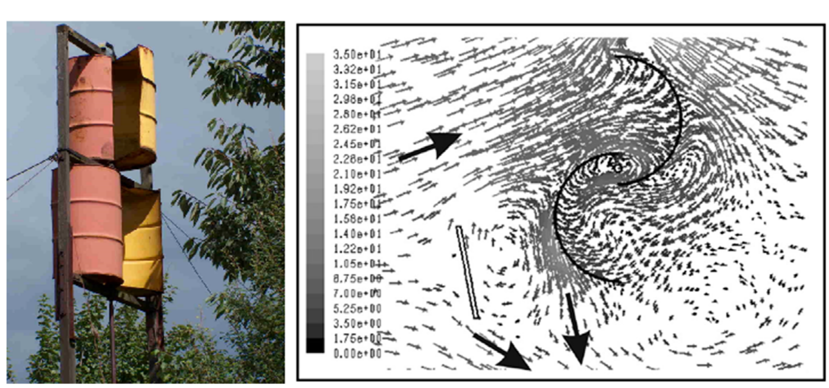

Fig. 23. Extremely low-cost Savonius wind turbine (left), and a diagram of a Savonius wind turbine with two blades and a deflector sheet (right) [38].

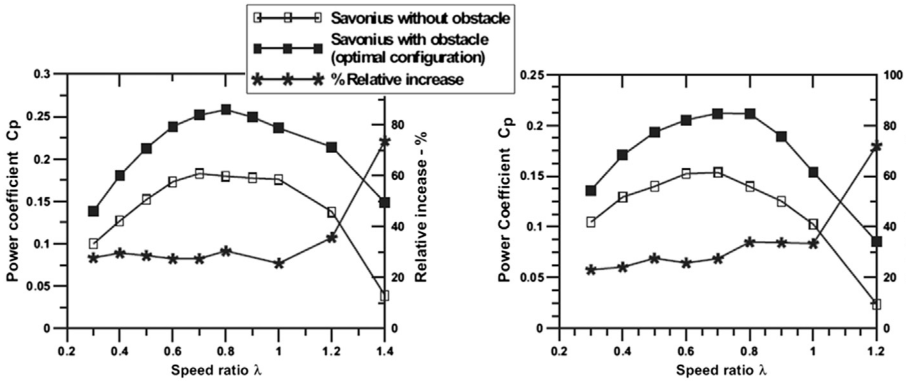

Fig. 24. Power coefficient of a Savonius wind turbine with two (left) and three (right) blades with and without a deflector sheet [38].

Fig. 25. Helical Savonius wind turbine with three blades.

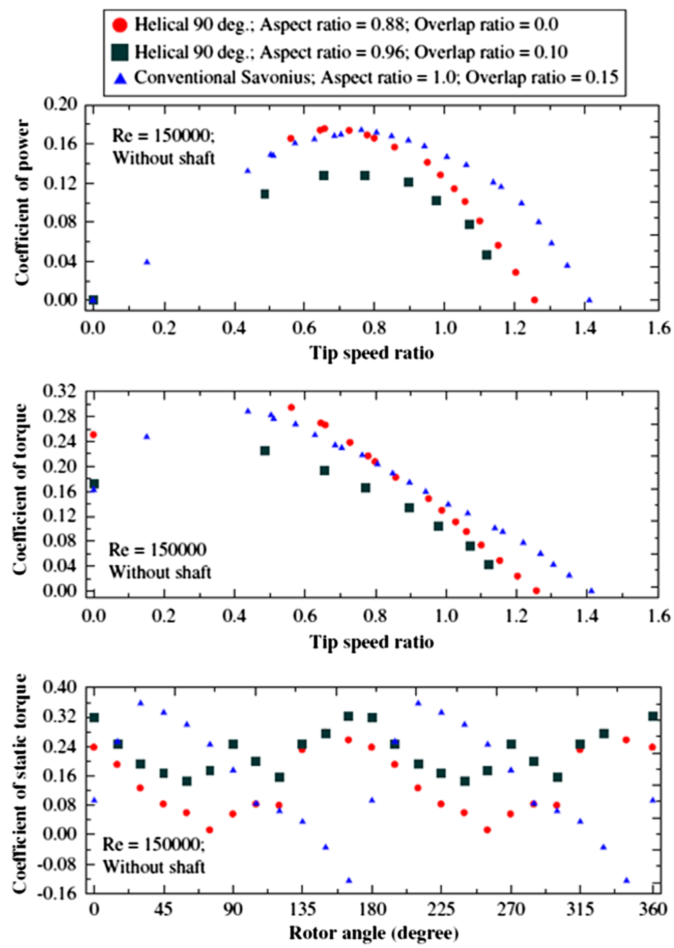

Fig. 26. Coefficients of power, torque and static torque for a two-blade Savonius wind turbine with both helical and conventional blades [39].

(Fig. 23 right). The results show that the deflector sheet installation increases the wind turbine efficiency considerably (Fig. 24) and that the power coefficient is higher in the case of the rotor with two blades.

Kamoji et al. [39] conducted a study of the helical Savonius wind turbine (Figs. 25 and 26) show that both the power and torque coefficients are slightly higher in the helical design than in the traditional Savonius under low wind velocity conditions. The great advantage of the helical blades is that the coefficient of static torque is always positive for all incident angles (Fig. 26). The main disadvantage is the higher complexity of the construction, which implies a cost increase [38].

As mentioned previously, the low coefficient of power of the Savonius rotor is the most important disadvantage; hence, the improvement of this factor is important to the development of this technology [37,38]. In Table 3, a summary of the main improvements to increase the performance of the Savonius rotor is shown.

Müller et al. [40] propose a vertical-axis, resistance-type wind turbine (Fig. 27). The main advantages are the simplicity of the design, which implies a lower cost of construction, and the high efficiency (Fig. 28), approximately 48–61%. This system can be part of a wind–solar hybrid [41,42]. A disadvantage is that because the wind turbine is partially covered, the sweep area is lower and it has a fixed direction. This problem can be solved by adding a moving power-augmentation guide vane (PAGV) that surrounds the turbine and orients the inlet air flow, which is capable of increasing the rotor rotational speed by a factor of 1.75, the torque by a factor of 2.88 and the power output by a factor of 5.8 [43].

Table 3
Improvements to increase the performance of Savonius wind turbines [37].

Design modification	Gain	Comments
Helical rotors	Improvement of static torque	Complex design, high cost
Deflector plate	20%	No further details since 1992
Twisted-blade	27% relative	Complex design, high cost
Guide-box tunnel	50% (3 blades)	Complex design
Modified Savonius	60% in static torque	Expected vibration problem
Guide vanes	Depends on wind speed	Problems for large tip-speed
Obstacle plate	15% on peak value	Small parameter space used

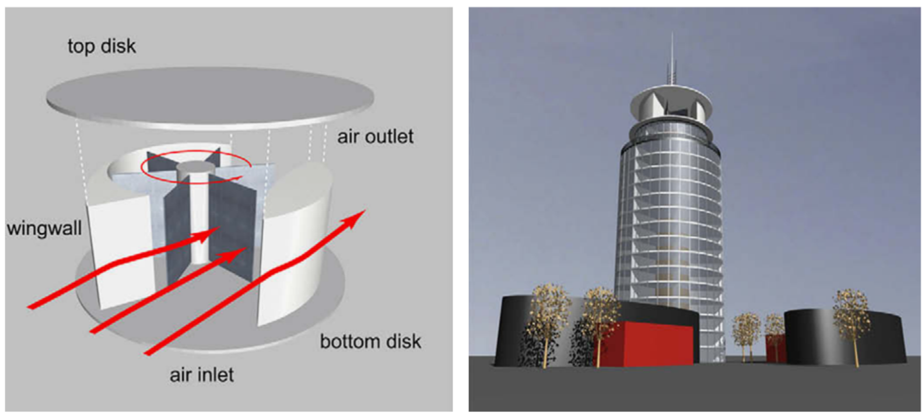

Fig. 27. Vertical-axis resistance-type wind turbine [40].

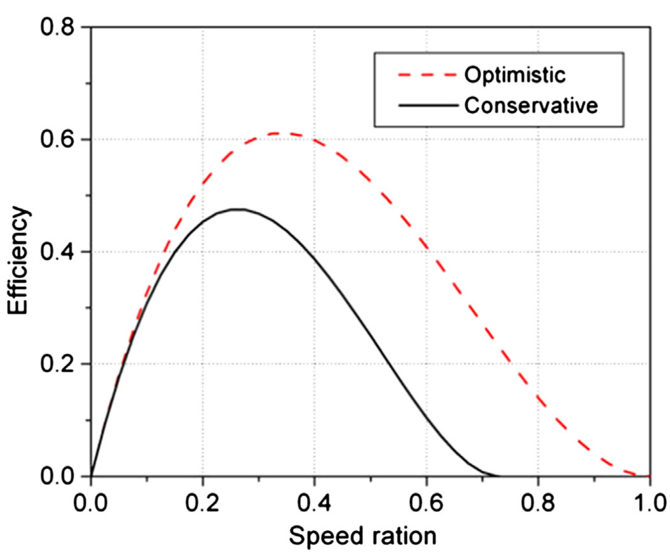

Fig. 28. Efficiency of vertical-axis resistance-type wind turbines [40].

3.2.4. Ducted wind turbine

Grant et al. [44] present a ducted wind turbine, installed on the edge of the building roof (Fig. 29). The power coefficient can be higher than the Betz limit, even exceeding unity (Fig. 30). However, both the high cost/power ratio and the fixed direction make it difficult for this technology to compete against other alternatives [44]. Furthermore, this kind of wind turbine can only operate with a perpendicular wind direction.

Fig. 31 shows the superposition of a ducted wind turbine on the edge of the building roof for an incident velocity of 1 m/s. The represented conditions are appropriate for turbine operation, although this kind of wind turbine can only operate with a perpendicular wind direction, as in the simulation.

Fig. 29. Ducted wind turbine on the edge of the building roof [44].

4. The significance of the multidirectional character of the urban wind for turbines

The results of the qualitative analysis show that the use of a HAWT on the central area of a flat building roof presents problems from the aerodynamic point of view because the multidirectional wind is incompatible with normal turbine operation. Moreover, the HAWT is subjected to loads beyond its design specifications.

In contrast, because of their omnidirectional character, VAWTs (including horizontal Darrieus and ducted wind turbines) have aerodynamic advantages in urban environments. Both horizontal Darrieus and ducted wind turbines have additional aerodynamic advantages in building roof applications, where the multidirectional condition of the urban wind is more favourable than the unidirectional wind conditions.

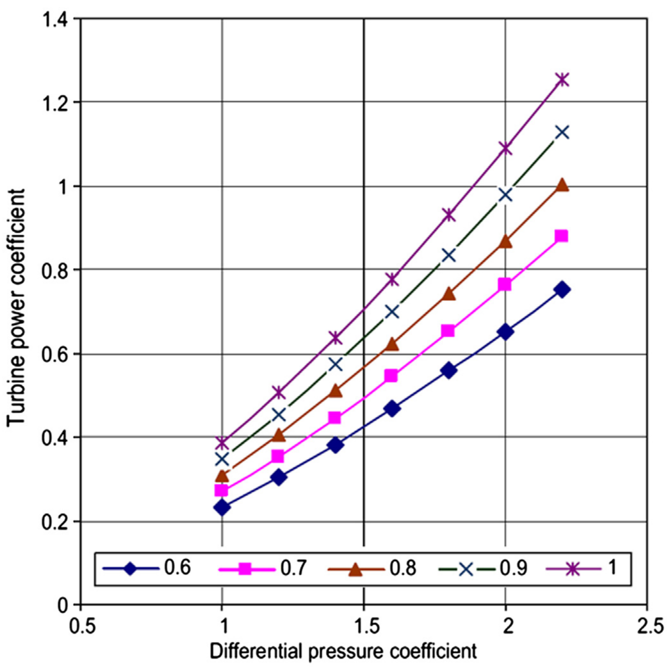

Fig. 30. Power coefficient vs. the differential pressure coefficient of a ducted wind turbine for various values of the speed coefficient [44].

In urban power applications, the multidirectional character of the wind plays a decisive role, even more than the incident velocity. For this reason, the VAWT technology is of great interest.

The results of this analysis are applicable to the case of buildings with a lower relative length, including skyscrapers, because of a vorticity phenomenon that occurs on the roof [7]. The vertical edges are also of interest for wind power exploitation in high-rise buildings because of the concentration factor of the velocity around them [36], as shown in Fig. 19 right.

The results can be extrapolated to other roof shapes. Both pyramidal and pitched roof shapes present a multidirectional character of the wind even greater than that of the flat roof [6].

5. Conclusions

In this work, a literature review of the main perspectives and proposals for wind power exploitation in urban environments has been given. With the obtained information, the characteristics of the urban wind and the proposed solutions for its exploitation have been analysed. This analysis provides an understanding of the particular characteristics of the urban wind, and it gives a wide overview of the various technologies that have been proposed for wind resource exploitation in this complex environment, with many challenges and opportunities for development.

In the urban environment, the multidirectional character of the wind plays a more important role than the incident velocity. The velocity fields have a highly multidirectional component, which requires both qualitative and quantitative analyses of the wind turbine behaviour under these conditions. The normal test conditions for these systems are a unidirectional incident wind and a stable atmosphere. Because of this, to analyse the effect of the multidirectional conditions of the urban wind on the turbines, a CFD simulation of the air flow around a building has been conducted. The results of the simulation show velocity fields in agreement with the highly multidirectional component.

The sections of various kinds of wind turbines have been superimposed over the velocity field obtained from the simulation, and their aerodynamic behaviour has been analysed in a qualitative manner.

The obtained results show that HAWTs have higher performance in flat terrain applications or similar conditions such as on large structures. The main advantage of HAWTs is their high efficiency, but their great disadvantage is that they can only

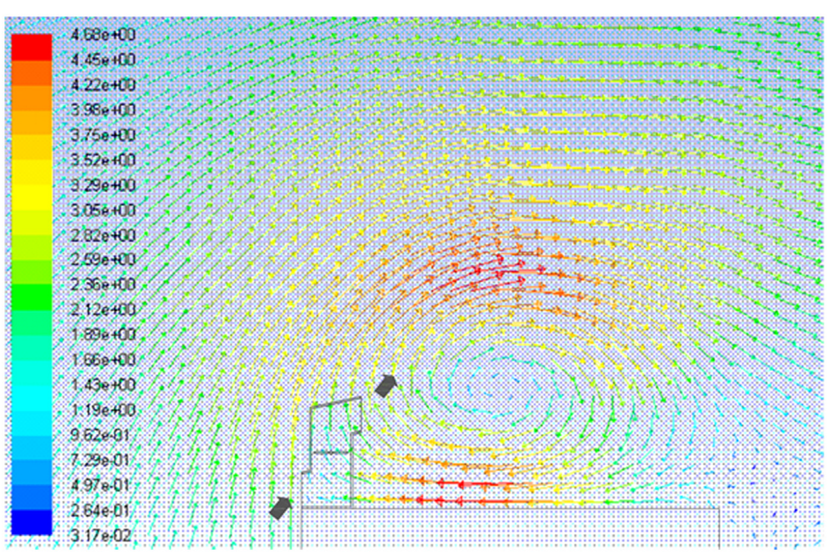

Fig. 31. Superposition of a ducted wind turbine on the edge of the building roof for an incident velocity of 1 m/s.

operate under unidirectional wind conditions, so they are less appropriate for urban environments.

Because of their omnidirectional character, VAWTs are more suitable in areas with a higher building density—they can accommodate multidirectional and turbulent conditions. Both horizontal Darrieus and ducted wind turbines have better behaviour on a building roof than in flat terrain conditions, although they have technical and economic disadvantages.

Both pyramidal and pitched roof shapes present a higher multidirectional character of the wind than flat roofs. These shapes are less desirable for wind exploitation than the flat roof because the wind velocity on the roof decreases for a wide range of incidence angles, causing a decrease in wind potential.

The vertical edges are also a potential site for wind power exploitation in high-rise buildings because of the concentration factor of the velocity around them.

The wind energy in the urban environment is a resource with great potential that is currently wasted. The main advantages of its exploitation are:

- It creates an electricity supply in isolated areas far from the power grid, adapting itself to renewable sources and to the supply requirements. Either HAWTs or VAWTs can be chosen according to the topography and the wind characteristics.
- The energy is generated in a distributed manner (distributed energy micro-generation), avoiding both transport and distribution electrical losses.
- It allows the energy self-consumption to be either isolated or connected to the power grid. In the case of Spain, for example, self-consumption is regulated (RD 1699/2011), and future regulations to allow the injection of the excess electricity into the power grid are expected. Then, the electricity generated but not used at that moment will be injected to the power grid and measured by means of a bidirectional electricity meter. Therefore, the use of batteries is not necessary, decreasing both installation and maintenance costs. A balance between consumption and generation will be determined at the end of each month, yielding the net electricity consumption or generation.
- It can be combined with photovoltaic energy into hybrid facilities.

Micro wind generation in the urban environment is viable. The greatest impediment to its development is the lack of adequate regulation. The development of intelligent power grids will facilitate, from the technical point of view, distributed generation, and it will enhance the requirements of both small wind and photovoltaic facilities.

The conclusions of this work show the necessity of further work in the urban wind energy field. Specifically, the development of both qualitative and quantitative tests of different wind turbines are of great interest, mainly VAWTs (which present some advantages in urban environments), under multidirectional wind conditions because these are the actual conditions that the turbines are subject to in urban environments. Future work will enhance the proposed solutions for the urban wind exploitation, a field with many opportunities for development in a future with many uncertainties about the energy supply.

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